2-micron Coherent Doppler Lidar For Space-based Global Wind Field Mapping

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***Abstract*- A space-based 2-micron Coherent Doppler lidar can have a significant impact on climate research and numerical weather forecasting. This paper describes the key challenges of deploying such an instrument in space, and provides a status of the technology development activities.**

I. INTRODUCTION

NASA's desire to measure global wind fields with a Doppler lidar dates back to the first demonstration of Coherent Doppler Lidar (CDL) in 1967. Since then many coherent lidar systems have been developed and employed in a wide range of scientific and operational applications. These applications include climate and severe storm research, aviation safety and efficiency, and a number of military applications such as target identification, parachute drop, and ballistic trajectory control. The most dramatic technology leap probably occurred in the early 1990's due to the emergence of 2-micron solid state laser technology. The earlier CDLs were based on CO_2 gas lasers operating near 10 microns wavelength. The solid state laser technology offered several key advantages over the CO_2 lasers that drastically increased the utilization of CDLs. Solid state laser technology allowed for the development of more compact and efficient systems that can operate autonomously. Operating at a shorter wavelength, solid state laser technology eliminated the need for consumables and cryogenically cooled detectors while providing more accurate wind velocity measurements with higher spatial resolution.

NASA has played a major role in the advancement of CDL technology because of its potential in both aviation and space applications. NASA's motivation for space applications arises from CDL's ability to accurately measure wind profiles in earth's boundary layer and troposphere, and to provide global coverage, including oceans and remote regions, with high spatial resolution. This measurement can have significant impact on climate research and can substantially improve weather forecasting [1].

II. LIDAR INSTRUMENT

The system diagram depicted in Fig. 1 illustrates the design and operation of a solid state CDL instrument concept under consideration by NASA for future launch. The transmitter laser consists of a pulsed oscillator laser generating moderate pulse energy of the order of 100 mJ at 12 Hz, a power amplifier scaling the pulse energy to at least 2 J, and a low power continuous wave (CW) master oscillator (MO) laser. The MO laser is highly stable and generates about 25 mW of power at a single frequency. Part of the MO output is used for injection seeding of the pulsed oscillator laser to generate single frequency pulses at a fixed offset from the MO laser frequency. After being amplified by the laser power amplifier, the transmitter pulses are directed toward a beam-expanding telescope. In the design concept of Fig. 1, the telescope is rotated about its axis to also serve as the scanner generating a conical scan pattern in the atmosphere. The telescope is approximately 75 cm in diameter and has an off-axis design to avoid obscuration and diffraction by the secondary mirror and to allow scanning of the laser beam. The laser beam is scanned in a step-stare fashion, as opposed to a continuous pattern, to accommodate optimum placing of the laser pulses in the atmosphere for best measurement accuracy and representativeness. Step-stare scanning also eliminates the need for an optical de-rotator for correcting the signal misalignment due to the continuous motion of the telescpoe during the pulse round trip time, thus reducing the complexity of the instrument. For this concept, the telescope is held stationary during the firing and acquisition of several laser shots, and then it is moved to a new position on command for another set of laser shots. The laser beam is scanned 30^o to 45^o about the fixed nadir.

The backscattered signal from the atmospheric aerosols is collected by the telescope and directed toward the detector. The return signal is separated from the outgoing pulse through polarization discrimination using the combination of a quarter-wave phase retarder and a polarizing beam splitter. The return signal is mixed with the local oscillator (LO) laser beam at the detector. This generates an electrical signal at the difference frequency between the transmitted and return signal frequencies. In order to compensate for the large Doppler shift due to the spacecraft motion, and minimize the required bandwidth of the detector and receiver, the frequency of the LO laser is varied about the seed laser frequency with the azimuth angle of the conical scan. The LO laser is similar to the MO laser except it includes a frequency tuning mechanism, which is usually a PZT actuator controlling its cavity length. The unused part of the MO laser output is mixed with part of the LO laser output on a wideband detector to generate a control signal for locking the LO laser frequency to that of MO laser.

The receiver optical train includes a small 2-axis steering mirror referred as nadir angle compensator (NAC). The NAC, through an active control system, corrects for the misalignments due the change in the spacecraft inertial nadir pointing angle during the pulse round trip time.

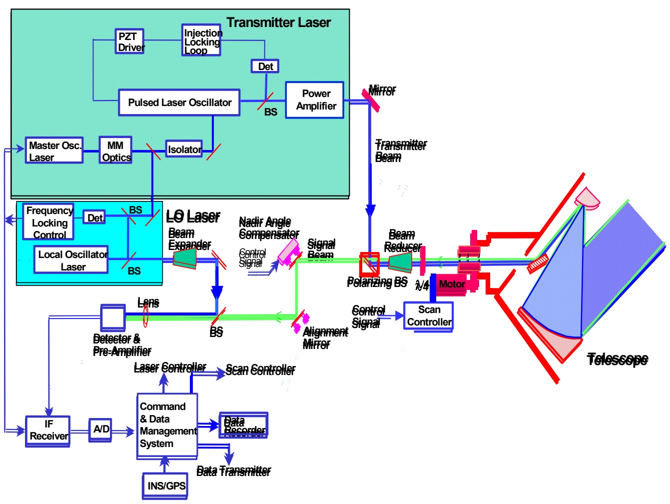

Figure 1. 2-Micron CDL System Block Diagram.

III. CDL TECHNOLOGY DEVELOPMENT

Despite a relatively long history and considerable potential benefits, CDL has not yet been deployed in space due to a combination of engineering issues unique to space environment and difficulties in meeting all the critical scientific objectives with a single affordable instrument. The key issues are power consumption, size and mass, laser pulse energy, reliability and lifetime, scanning laser beam, maintaining optical alignment, and pointing control and knowledge. In order to overcome these issues, further technology advancements in several areas, particularly the pulsed transmitter laser and scanning optics, are needed. NASA has been actively working on some of these technology areas toward a long lifetime instrument that can meet the major scientific and operational requirements. More recently, a new program was initiated in NASA named Laser Risk Reduction Program (LLRP) that focuses on the development of a number of high-power laser systems for space-based lidar applications including 2-micron solid state laser for global wind profiling. Another focus area of the LLRP is advancement of the laser diode arrays for pumping solid state lasers. Laser diode arrays are a critical component of solid state laser systems that essentially establish the lifetime and reliability of lidar missions. In addition to the efforts on the 2-microm transmitter laser and the laser diode pump under the LLRP, NASA is also working on other critical CDL technology areas at a lower level.

A. Transmitter Laser

The pulsed transmitter laser is the heart the CDL instrument dictating much of the instrument design configuration. At the same time, a space-based CDL instrument imposes stringent performance requirements on the transmitter laser that must be maintained in the harsh environment of space with limited physical resources. For more than a decade, NASA has been working diligently toward the development of 2-micron solid state laser technology that can provide sufficient pulse energy at an acceptable repetition rate while meeting CDL's stringent spectral purity and stability, and addressing space accommodation issues.

Scientists at NASA/LaRC have developed a quantum mechanical model that can predict the performance of different laser materials. There are virtually thousands of different possible laser materials and compositions that can generate 2-micron radiation. Growing and testing even a fraction of potential laser crystals is impractical. However, the quantum mechanical model allows for identifying the most promising candidates and determining their optimum concentrations. This analytical modeling resulted in the selection of a Ho:Tm co-doped fluoride lasing material that proved to be a successful approach.

The laser utilizes a master-oscillator-power-amplifier (MOPA) design. Efficient amplification is important since the amplifier will consume most of the available electrical power. Fig. 2 shows a block diagram of a 2-micron MOPA laser system. The diode-pumped, Q-switched power oscillator uses a ring resonator configuration. This laser is injection-seeded by a single frequency CW Ho:Tm laser. The amplifiers are operated at double-pass amplification configuration. Double-pass or multiple-pass operation can help to extract more pulse energy and improve the efficiency of the amplifiers. Recently, a 2-micron laser with 1.05 J Q-switched output energy was successfully demonstrated. The laser operates with a double pulse format to further improve the system efficiency [2]. This was the first demonstration of a Q-switched 2-micron laser breaking the 1 J barrier.

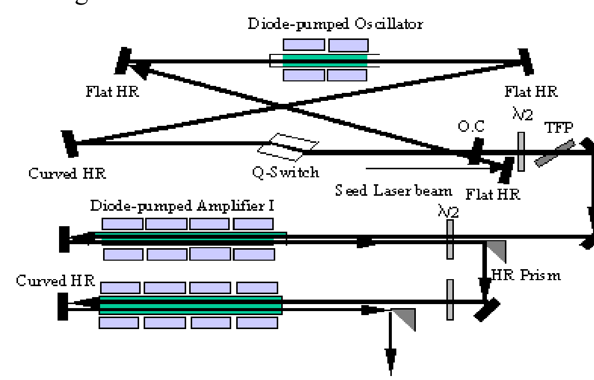

Figure 2. CDL Transmitter Laser.

B. Laser Diode Pump

Laser diode arrays are a critical component of a solid state laser that are used as the pump source for energizing the lasing media in order to generate a high power coherent laser beam. The lifetime and reliability of any lidar instrument are basically established by their pump laser diodes. Therefore, any improvement in their reliability will have a major impact on mission lifetime, risk, and cost. Unfortunately, limited commercial availability combined with lack of statistical data required for screening and predicating the reliability of high power laser diode arrays presented many challenges for past NASA laser missions. For these reasons, NASA initiated an effort under the LLRP to address the laser diode issues. A major part of this effort focuses on high power laser diode arrays used for pumping 2-micron lasers.

The requirements levied on laser diode arrays by high pulse energy 2-micron solid state lasers are particularly challenging compared with widely used 1-micron Neodymium-based lasers. The 2-micron lasers require much longer pump pulse duration than 1-micron lasers, which causes the laser diode active material to experience drastic thermal cycling. This translates to a much shorter lifetime compared to the laser diodes used for 1-micron lasers. In order to increase the lifetime of these long-pulsewidth laser diodes, different laser diode packaging technologies are being pursued toward improving their thermal characteristics. An elaborate laser diode characterization facility is also currently being developed for addressing the specific issues associated the laser diodes for pumping 2-micron transmitter lasers.

C. Scanning Telescope

On command pointing of the CDL beam off the nadir along different azimuth angles presents a major challenge for both the instrument and its platform. The only viable approach for scanning the laser beam, that can be considered for a relatively near term mission, is to rotate the telescope. For this approach to succeed, the weight and size of the telescope has to be kept to a minimum to permit quick starting and stopping of the rotation without resorting to massive momentum compensation wheels and drawing excessive peak power by the rotation motor. However given the practical constraints on the transmitter laser, the telescope must have a significant size to achieve the desired sensitivity. For the design point considered here, the telescope has a diameter of about 75 cm. Conventional telescope designs with glass optics and metal structure, meeting stringent CDL optical quality and stability requirements, cannot provide a cost effective option.

There are several approaches for achieving lightweight telescopes. In the past, lightweighted beryllium mirrors were successfully used for space-based lidar instruments. However the use of beryllium mirrors for a space-based CDL is not desirable because of its relatively high thermal expansion coefficient and its fabrication limitations in implementing an off-axis design due to its toxic nature. Coherent detection is highly sensitive to aberrations in the signal phase front, and to relative alignment between the signal and the local oscillator beams. This points to the use of unconventional designs and advanced materials that can produce a thermally-stable off-axis telescope meeting the optical quality requirements of CDL instrument.

Currently, a novel approach being pursued that is based on using nickel alloy shells to form the telescope optical surfaces and structure. The use of same material to produce a thermally-stable compact CDL telescope has already been demonstrated [3]. Fig. 3 shows the CDL scanning telescope concept. This telescope concept utilizes the same general optical design as the earlier athermal telescope. The telescope optical surfaces and structure are made of relatively thin hollow nickel shells. The fabrication process starts with making aluminum mandrels for each individual part. The mandrels of the primary and secondary mirrors are diamond turned for high surface figure accuracy and quality. The mandrels are coated by a layer of nickel using a plasma spray process. The replicated surfaces are then separated and polished. Finally, the optical surfaces are gold-coated for high reflectivity. Recently, a 10 cm experimental nickel shell flat mirror has successfully demonstrated the capabilities of the plasma spray technique in generating optical surfaces and mechanical parts.

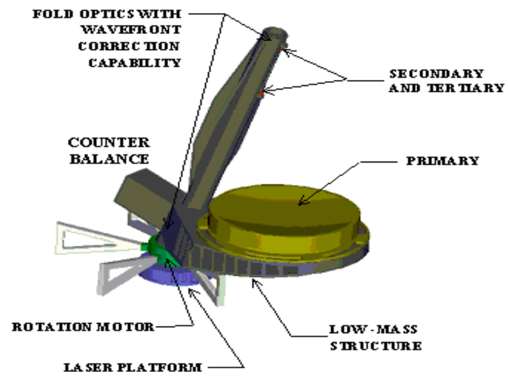

Figure 3. CDL Scanning Telescope Concept.

D. Receiver

Earlier analytical work has shown that by integrating the CDL receiver components significant improvement in the lidar sensitivity and robustness can be achieved [4]. The integrated components include the detectors, local oscillator diode laser, optical mixer, the radio frequency amplifiers and electronics. The integration of these components will result in higher sensitivity, more compact size, and increased robustness in severe thermal and vibrational environments. The integrated receiver will also allow for true optimization of the receiver operating and design parameters, and the use of more efficient receiver architectures such as dual balanced-detectors.

One of the advantages of the integrated receiver is the minimization of parasitic capacitances and inductances associated with the detector and pre-amplifier packages and their leads. The lidar receiver sensitivity improvement resulting from elimination or reduction of the parasitic capacitances and inductances has been experimentally shown to be about 2 dB for a 2-micron CDL. This experiment led to the design of an optimized integrated receiver using a dual balanced-detectors configuration. This receiver uses a custom-designed transimpedance amplifier optimized based on the detector characteristics parameters resulting in additional sensitivity improvements of 1-2 dB. Current work also includes the development of a narrow linewidth, tunable, diode laser at NASA/JPL to serve as the local oscillator in the receiver integrated package.

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